Executive Summary: Electric Pipelines for North American Power Grid Efficiency & Security

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One thing holding back development of wind and solar energy in America is the lack of capability to send electric power around the country. The best wind and solar sites are often far from major electrical energy markets. Although the present power grid allows electric utilities to send power hundreds of miles, it is not capable of transporting power efficiently from coast to coast. Overhead power lines are simply not able to transmit significant electric power coast-to-coast in the USA. Underground power lines ("electric pipelines") would however be capable of transporting power all around the USA. A grid based on these electric pipelines would improve the security and stability of our electric power system (against both accidents and terrorism), and would facilitate wind and solar power becoming a much larger part of our energy mix.

The present electric power grid is vulnerable to being crashed by very low tech methods. Our grid can be brought down by the simultaneous failure of two major power lines during a period of high power demand, as occurred in both the 1964 and 2003 East Coast regional blackouts (sabotage was not involved in either of these events). It would be simple for saboteurs to duplicate the events that caused the August 14, 2003 blackout given our present electric grid design. A network of electric pipelines would make our power system far more resistant to being brought down by sabotage, and the electric pipelines themselves could be far more resistant to sabotage than overhead power lines.

The degree to which distant regions can share power has a direct effect on the need for new power plant construction. Electric pipelines, by increasing the distance over which power can be shared in North America, would reduce the need for new power plant construction dramatically, saving more than $100 billion in new power plant construction costs (enough to pay for the electric pipeline grid).

A network of underground electric pipelines would have far fewer aesthetic effects than the massive overhead power lines that have become all too familiar throughout the developed world. At the same time, underground electric pipelines would produce far less EMF (electromagnetic field) effects than overhead power lines (some epidemiologic studies have suggested that EMF from overhead power lines increases the risk of certain cancers for people living near the power lines).

One particularly relevant effect of a North American grid based on high-capacity electric pipelines would be to make it practical to send solar-generated electricity from the American Southwest to East Coast cities for peak power. (The energy demand for air conditioning on the East Coast correlates very well with the available power from solar electric generators in the American Southwest.) This would have very positive effects on reducing pollution and greenhouse gas emissions; this is just one of several such positive environmental effects.

“Electric pipelines” as an innovative technology for electrical grid security, development of renewable energy sources, and energy conservation

Our present electrical grid is vulnerable to being brought down by very low tech methods that could easily be used by terrorists. The fact that this has not yet happened should not be very reassuring to anyone, since the August 14, 2003 East Coast blackout showed that simultaneous failure of a few power lines can cause a ripple effect that can crash the grid over a wide area (not the whole country, but an entire “synchronous region” can be crashed by only a few simultaneous outages of major power lines during a period of high power demand). In the 2003 outage, a chain reaction began with two major power lines in Ohio that shorted out due to vegetation contacting the wires (the wires had sagged because they were carrying very high current, due to high demand); within minutes the disruption caused 21 power plants to shut down, leaving millions of people without power. This vulnerability has long been known to electrical system experts, and it may be only a matter of time until it is exploited by terrorists.

Perhaps the best way to improve resistance of our power grid to interruption by terrorist acts would be to put major power lines underground. These underground power lines (“electric pipelines”) could have lower electrical resistance than present overhead power lines, and could operate at higher voltage, resulting in more efficient transportation of electrical energy. A network of electric pipelines is the best way (I would argue the ONLY way) to implement a continental-scale power grid. A North American grid that would be capable of moving hundreds or thousands of gigawatts of power coast-to-coast would produce complex economic and political effects which would affect generation methods and efficiency. A North American grid would encourage solar, wind, biomass, geothermal, and hydroelectric power development by greatly improving market access for power generated in remote areas. To take the specific example of wind power, a North American grid would make wind power more reliable, since by tying together numerous different wind “hot spots,” the probability of low available wind power due to weather conditions becomes much less likely. Such a grid would also reduce opposition to nuclear reactors by allowing them to be sited far from population centers. These effects would reduce greenhouse gas emissions substantially.

A strongly interconnected North American electricity grid would tend to decrease pollution, insofar as the least efficient (and therefore most polluting) generators would tend to be shut down (completely or in part) by competition with more efficient generators. The key missing element at present that prevents the development of continental scale (and eventually global) strongly connected power grids is a practical means to efficiently transport tens to thousands of gigawatts of electric power coast-to-coast, with acceptable costs and environmental impacts.

If it were possible to bring solar power from Arizona, New Mexico and Texas to East Coast cities, solar power would be cost competitive with daytime peak power generated by gas turbines today. Solar power installations in the US southwest cannot presently send power east, which

effectively rules out major (strictly economically-driven) development of solar power; given present economics and solar technology, solar energy facilities would be built in the US southwest with private capital if the power could be sent east to be sold as "peak power."

We have nearly reached the theoretical limit of the conventional, overhead transmission line, and it is obvious that such lines will never be capable of linking the coasts of North America, let alone the Earth as a whole. Furthermore, overhead power lines are very vulnerable to terrorist attacks. The technology of electric power transmission is due for an overhaul. Overhead transmission lines grow more controversial each year, while at the same time, the economic incentive to transport bulk power grows each year.

Because of the strong economic incentive to transport western US electricity east (and similar incentives around the world), new technology is bound to arise that will make it possible to transport bulk electric power on a continental and eventually even on a global scale. The political question is, should this technical evolution be promoted and accelerated as a matter of policy? Would improved capability to transport electrical energy produce significant benefits for the US and world economies in the next several decades? I believe the answer to these questions is yes.

Any technology to transport massive amounts of electricity coast-to-coast must be reliable, rapidly repairable, and redundant in order to guarantee continued supply in the face of possible accidents, geological or weather events, or terrorism. Redundant implies at least two independent power lines must connect the East Coast to the West Coast. Figure 1 shows one particular layout of a North American grid that meets the need for redundancy via a loop design. The design of Figure 1 is singly redundant from the East Coast to the West Coast, and has additional redundancy around the Great Lakes and eastern US. In order to reach all the major cities in North America, smaller connectors between the major loop and cities that are off the loop would be required. The grid layout shown in Figure 1 would be a desirable implementation for any grid to move power around North America through wires regardless of design details, such as superconductor- versus conventional conductor-based electric pipeline designs. Even overhead power lines, if they became feasible for interconnecting the coasts due to a future technological breakthrough, would also probably follow a grid layout like that of Figure 1.

***Figure 1: Map of N. America, showing a major loop that runs down each coast, connecting in the North from Seattle to New York through Chicago, Detroit, and Cleveland, with spurs tying in major cities and hydro power sources that are off the main loop, such as Vancouver, Las Vegas, Denver, Boston, Montreal, the Canadian Rockies, and Quebec hydro power. A loop goes north of the Great Lakes through Winnipeg, Ottawa, and Toronto, so that the service is doubly redundant in this region. The main loop goes south along the East Coast, passing near Atlanta, New Orleans, Houston, Dallas, Phoenix, and San Diego. A Mexican/South American spur goes south to Mexico City. The line is singly redundant for the entire loop, and doubly redundant in

some areas. A connector runs from Chicago to New Orleans through Saint Louis, and Nashville...sketch in additional connectors as needed to service most cities.

AC vs. DC & Overhead vs. Underground Power Lines

Ever since the earliest examples of long distance electric power transmission, overhead transmission lines have been the preferred method for transporting large amounts of electric power. As the length of any conventional transmission line increases, both the energy transfer capacity of the line and the efficiency of energy transfer decrease. The main ways to fight this are to increase the transmission line voltage, and/or to increase wire diameter. Up until about 1959, only AC power could be readily changed from one voltage to another (via transformers, which only work for AC power). Now however, AC/DC converters that are comparable in efficiecy (~98%) to transformers are readily available. Today, all the highest capacity longest-distance power transmission lines in the world are overhead high voltage DC lines (HVDC).

There are different trade-offs for AC versus DC power transmission. For example, voltage can only be taken up to about 500,000 volts (500 kV) for an overhead AC power line because beyond that, power dissipation through dielectric loss becomes severe. Voltage for DC overhead power lines can be taken up to double the maximum AC voltage, to about 1000 kV (one million volts from ground potential; 2 million volts between the conductors); beyond that, power dissipation through corona discharge becomes severe. Underground DC power lines can use even higher voltage, and can be quite large; the main factors limiting size and design details are the need to insulate the conductor and to dissipate heat. Wire diameter is limited for AC transmission lines, whether overhead or buried, due to the “skin effect” that prevents an AC current from penetrating to the center of a large wire, whereas a DC line can be arbitrarily thick. For these and other reasons, underground high capacity power lines are necessarily DC.

The simplest way electric power could be sent coast to coast is to build power lines based on conductors with much lower electrical resistance than any long distance power lines in service today. These “electric pipelines” can be either conventional conductor or superconductor-based, in principle. The superconductor approach to electric pipelines has gotten some press and research interest, but is not technically ready to deploy yet. There is also a more pedestrian way to decrease the electrical resistance of a power transmission line: use more conductor.

A long range transmission project today typically will use around 1 to 3 cubic meters of aluminum per kilometer in the transmission wires themselves. The largest elevated transmission project to date is a huge Brazilian transmission line from the foothills of the Andes to Rio De Janeiro, which uses about 7 cubic meters of aluminum per kilometer. This DC power line makes it possible to deliver about 7,240 megawatts (7.24 gigawatts) of power after transmission 3,000 kilometers at 10% line loss. The towers are huge, and occupy a substantial right-of-way which

cannot practically be used for anything else. This power line does not have nearly enough transmission capacity to link the major eastern and western US power grids. In fact, it would require ~200 gigawatts of transfer capacity to meaningfully interconnect the two coasts of the US. To accomplish the interconnection with overhead power lines similar to the Amazonian transmission project would require at least 27 separate coast to coast lines. Such a project, even if it was economically feasible, is not politically feasible in the US because of the environmental and aesthetic impacts. On the other hand, an underground power line could link the Eastern and western US with a similar environmental impact to a gas pipeline.

The aluminum acquisition costs per se amount to less than 10% of the total cost for most long distance power transmission projects. Using a lot more aluminum (25-500 cubic meters of aluminum/kilometer) makes sense economically if energy savings and transfer capacity increases can finance the acquisition and installation of the extra aluminum. (There are plans to build a trillion dollars worth of new electric generating capacity in North America in the next twenty years; since long-range transmission capacity reduces demand, it is worth considering a continental power grid, based on purely capital cost savings. The further security, reliability, and renewable energy impacts makes such a project even more compelling.)

Inclusion of HVDC interconnects between portions of an AC grid makes the AC grid more resistant to the upsets that occur when a power line is suddenly removed from service. Sudden removal of a power line in an interconnected AC grid causes the phase of power arriving by two different routes to a single point to become asynchronous; if asynchronicity is bad enough, the initial upset can cause circuit breakers to blow at remote sites which share several interconnections to the power line which was removed from service. This can sometimes bring down the whole grid in a much larger area than that directly served by the power line that crashed (this happened in both the 1964 and 2003 East Coast blackouts). Unlike HVAC interconnections, HVDC interconnections are asynchronous, and tend to stabilize a primarily AC grid when a power line is suddenly removed from service, as by an accidental short or a broken line. Thus, connecting the existing AC grid to a DC grid will improve stability of the AC grid.

HVDC grids can be controlled either under amperage control or voltage control. At present, all major HVDC power lines operate under amperage control, which requires a nearly instantaneous synchronization of power injection and power removal between all the AC/DC converters connected to the grid. This becomes an unmanageable control problem above about 5 AC/DC converters connected to a single line. In order to build the sort of continental HVDC energy grid that would be required to share power across North America, it will be essential to operate the grid under voltage control (similar to the way a computer power supply works). Energy storage devices connected to the grid are an essential feature of such a control scheme. These storage devices either inject or remove power nearly instantaneously to maintain stable operating conditions (local voltage) for the grid. A byproduct of such a control scheme is added reliability

due to the presence of the storage capacity. There is a need for further research in this area before an HVDC grid can be built, but this is a soluble problem.

A feature shared by all electric pipeline designs is that to insure reliability, it must be possible to gain rapid access to the line anywhere along its course to perform repairs (for example, to repair a coolant leak or to replace a shorted out section of the line). This essentially requires that the electric pipeline (whether it is based on conventional conductors or superconductors) be installed in a service corridor, rather than being directly buried, so that it can be rapidly repaired. Such a high capacity, cross continental (or even global) power link would become so important economically that it would be intolerable to have the link out of service for a sustained time for repairs. The service corridor per se is a major portion of the total projected cost of a long distance high capacity power line (electric pipeline) project.

Electric pipelines are far more compatible with multiple uses of the transmission corridor than are overhead transmission lines. The service corridor could in principle be beneath a road; however, the possibility of attack by a truck bomb may mean that it would not be desirable to allow heavy traffic to use the corridor of an electric pipeline. Route planning for electric pipelines could allow for simultaneous uses for the right of way that would not be practical or desirable for overhead transmission lines, such as bike trails or future high speed rail lines. The greatly reduced EMF from underground DC power lines also implies that electronic telecommunications wires and occupied buildings can be in close proximity to the transmission line without electromagnetic interference or health concerns based on alternating magnetic fields.

Figures 2 and 3 illustrate the major trade-offs in regard to large HVDC projects. The lines in Figure 2 show the transfer capacities of various feasible power lines. The six lines represent different design voltages, from one to six million volts. The horizontal axis represents the actual amount of aluminum in the pipeline (including both the positive & negative conductors), expressed as cubic meters of aluminum/kilometer. The vertical axis represents transfer capacity in gigawatts; in this case the amount of power that can be transmitted 5000 kilometers with 10% line loss. (A large central station nuclear or coal-burning power plant typically produces about one gigawatt of power per unit.) It is interesting to note that much less aluminum is required to transmit a given amount of power as increasing voltage is used.

Notes: These assumptions apply to Figures 2 and 3, and Table 1:

1. Assumes pure aluminum conductors are at 100º Celsius (temperature affects aluminum conductivity slightly); a conservative assumption, since under normal operating conditions, the aluminum will be cooler.

2. Based on 90% transfer efficiency (10% line loss); line loss is less at lower transfer rates.

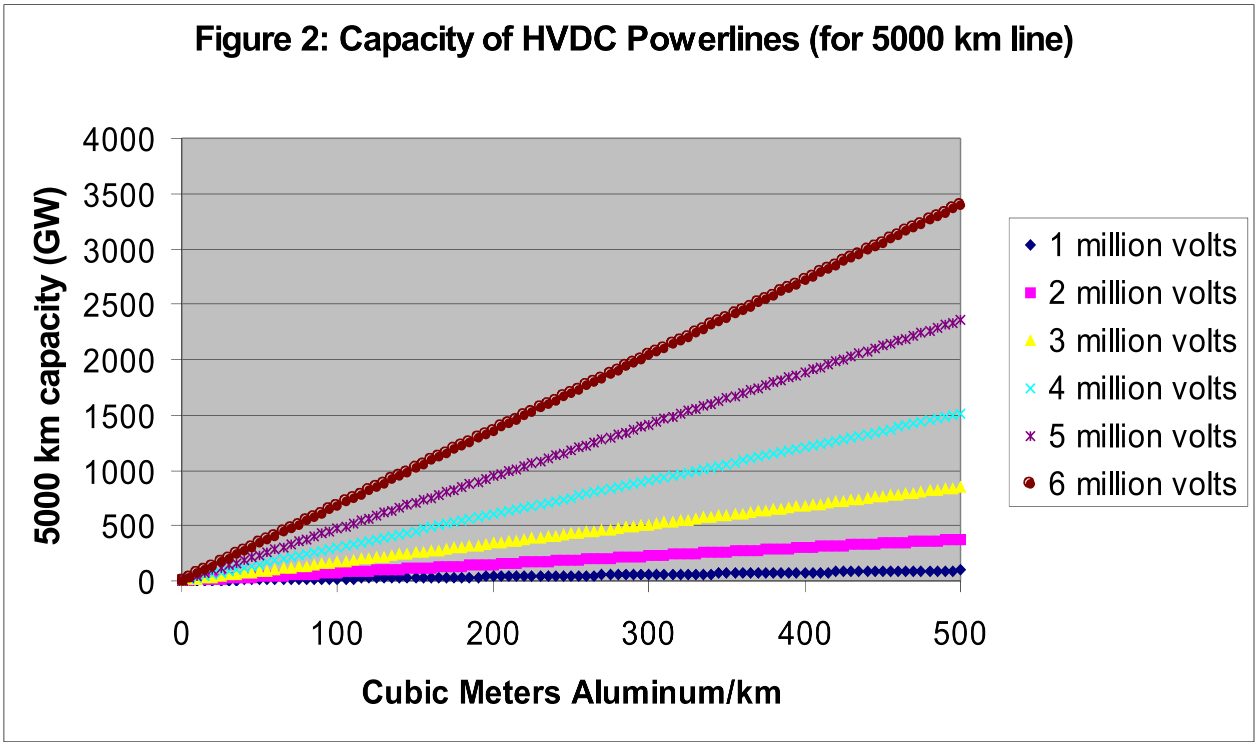
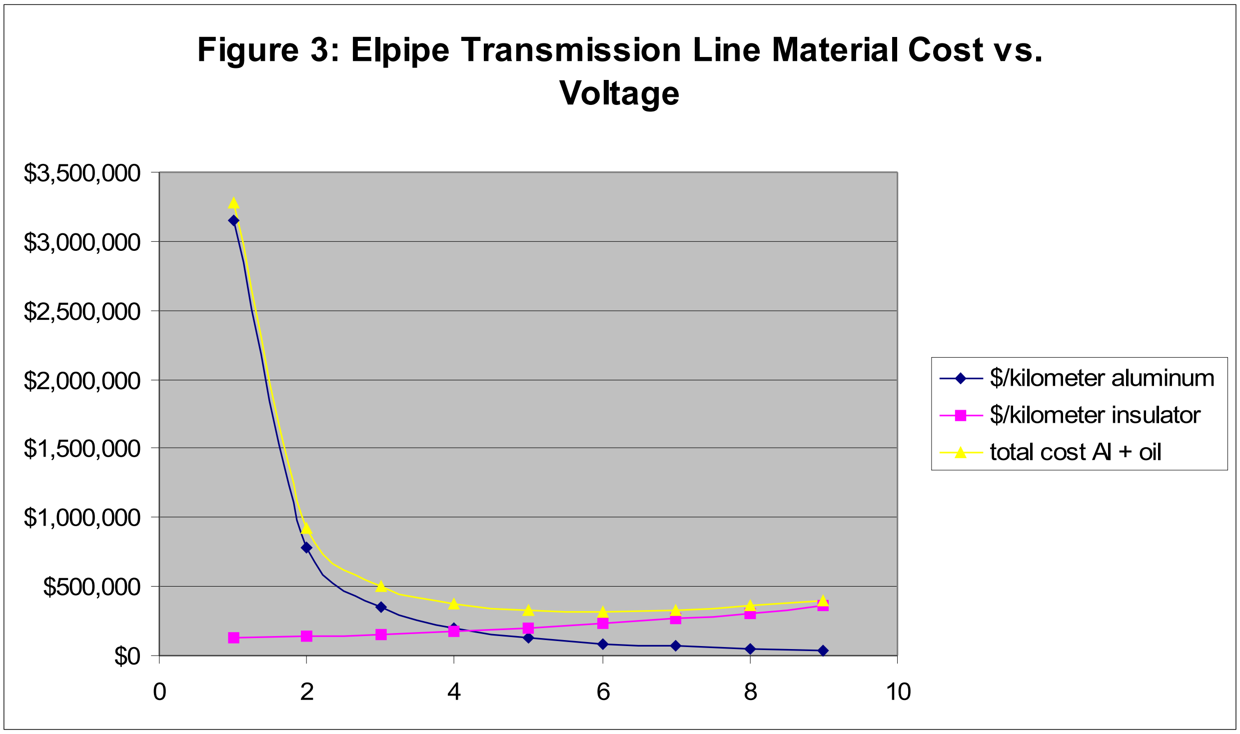


Table 1 and Figure 3 show estimated cost of aluminum, insulator (mineral oil), and the sum of both versus voltage required for the simplest possible design as a function of design voltage. This is a major portion of the project cost, but by no means a realistic cost estimate, since fabrication and construction costs, the cost of the corridor, and the cost of the numerous AC/DC converters has been neglected (Table 2 attempts to add in estimates for these other costs).

Table 1: Sizes of Elpipes to Deliver 180 GW 5000 Kilometers, 90% Efficiency

total megavolts	Aluminum m**3/km	insulator m**3/km	conductor diam., cm	insulator diam., cm	$/km aluminum	$/km insulator	total cost (Al + oil)/km
1	1060.0	97.7	82.15	1.85	$3,148,200	$129,013	$3,277,213
2	265.0	104.2	41.07	3.70	$787,050	$137,546	$924,596
3	117.8	115.0	27.38	5.56	$349,800	$151,767	$501,567
4	66.3	130.1	20.54	7.41	$196,763	$171,677	$368,439
5	42.4	149.5	16.43	9.26	$125,928	$197,275	$323,203
6	29.4	173.2	13.69	11.11	$87,450	$228,562	$316,012
7	21.6	201.2	11.74	12.96	$64,249	$265,537	$329,786
8	16.6	233.5	10.27	14.81	$49,191	$308,200	$357,391
9	13.1	270.1	9.13	16.67	$38,867	$356,552	$395,419

- Total volts means the voltage difference between the wires; this is twice the value that is usually cited (usually, voltage to ground is used to rate DC power lines).



Basis: Same assumptions as Figure 2 plus:

1. Aluminum costs $1.088/kg; electrical-grade mineral oil costs $1.50/kg.
2. 5000 kilometer power line, transmitting 180 gigawatts with 10% transmission loss.
3. White mineral oil was selected for the fluid insulator based on its good dielectric strength and low cost. This type of oil is non-toxic and thermally stable for long-term use at 100^{o} C under anaerobic conditions. A relatively conservative value of insulator strength (27,000 volts/mm) was used to calculate thickness of the insulator layer.
4. Small correction for curvature of the conductor was neglected.
5. Density of aluminum = 2.73 g/cc; mineral oil = .88 g/cc.

Figure 3 shows how conductor, insulator, and the total contribution of these two important costs to total line cost (neglecting the outer casing, corridor, and installation cost) change with voltage for HVDC electric pipelines. As voltage increases, the amount of aluminum needed to transfer a given amount of power goes down, while the thickness of insulation required on the conductors goes up. From low voltage up to about 3 million volts between the conductors, the cost efficiency of the power transmission improves rapidly with increasing voltage, because of the rapid decrease of the amount of aluminum required. From 4-9 million volts, the total cost for conductor + insulator are nearly constant, and the insulator costs more than the conductor. The least expensive transmission line (given the particular assumptions given above) occurs around 6

million volts line-to-line (3 million volts from ground). Other factors, especially the cost of the converter stations, imply that an operating voltage around 4 million volts (2 million volts from ground) would probably be preferred for a North American HVDC power grid based on mineral oil-insulated, aluminum conductor electricity pipelines.

Unlike superconductor-based options, the proposed electric pipelines are based on engineering principles and fabrication techniques that are well understood. Though construction of an electric pipeline network would indeed be a major undertaking, the project is doable without developing fundamentally new technology. Such a project could obviate the need for numerous new power plants, by allowing more efficient sharing of present resources. And, as mentioned earlier, such a grid would make certain environmentally desirable electricity generation methods much more feasible. As such, it would represent a large step towards reducing emissions from power plants. At the same time, the proposed HVDC grid based on electricity pipelines would improve both reliability and resistance of the electric power grid to terrorist threats.

Table 2 gives cost estimates for several different electric pipeline projects. Project 1 is a minimal sort of HVDC project for which conventional, direct-buried, polyolefin-insulated wires are used (several such projects are in operation around the world at present). Project 2 corresponds approximately to the Amazonian power line in Brazil that was previously discussed (the largest overhead power line ever constructed). Project 3 is a direct buried line that uses the same amount of aluminum/kilometer as the Amazonian power line (Project 2). Project 4 is a small electric pipeline, and Project 5 is a realistic scale electric pipeline designed to interconnect North America in a single redundant HVDC power grid. Clearly, there are a lot of approximations involved here, but the figure of $50 billion for a North American HVDC grid is believed to be "in the ballpark" for total project cost, excluding the cost of acquiring the land for the power line.

TABLE 2: Aluminum-Based Transmission Projects

Project number:	**1**	**2**	**3**	**4**	**5**
Project name:	**Direct buried wires, insulated with PE**	**Overhead Line like Amazonian project**	**Electric pipeline, directly buried**	**Electric pipeline, (mini-corridor)**	**Electric pipeline, (in corridor)**
project length	1,000 km	3,000 km	3,000 km	5,000 km	15,000 km
capacity, gigawatts	5.6	7.2	7.5	18	288
design voltage	1 million volts	2 million volts	2 million volts	2 million volts	4 million volts
electrical resistance	16 ohms	49.7 ohms	48 ohms	20 ohms	5 ohms
full capacity amperes	6,222 amps	4,024 amps	4,167 amps	10,000 amps	80,000 amps
max. heat output (kW/m)	0.56	.072	.074	.40	1.92
corona dissipation (EMF)	0	~0.5%	0	0	0
cubic meters alum./km	7.00	7.00	7.00	28	84
cubic meters oil/km	22.7	0	61.1	90.8	332
PROJECT COSTS					
aluminum[1] per km	**$20.800**	**$20,800**	**$20,800**	**$83,200**	**$250,000**
mineral oil[2] per km	0	0	$16,100	$24,000	$87,700
other materials per km	$14,000	$21,200	$21,100	$10,800	$20,000
fabrication per km	$50,000	$84,000	$100,000	$120,000	$150,000
installation per km	$145,000	$54,000	$150,000	$165,000	$660,000
installed conductor/km	**$231.,000**	**$180,000**	**$308,000**	**$403,000**	**$1.17 million**
total conductor cost	$231 million	$270 million	$600 million	$1.8 billion	$16.9 billion
converter stations	$560 million	$724 million	$750 million	$1.8 billion	$28.8 billion
PROJECTED COST	**$791 million**	**$996 million**	**$1.35 billion**	**$3.6 billion**	**$45.7 billion**
aluminum as a percent of project cost (excluding land)	9.0%	11.5%	7.1%	21%	21%

FOOTNOTES:

(1) Cost of aluminum is assumed to be $2970/cubic meter

(2) Cost of mineral oil assumed to be $264/cubic meter

The electric pipeline installation method must allow for rapid repair in case of a fault condition, and must also provide a backup circuit to handle the load during repair of a particular circuit. The backup circuit can be parallel, but preferably would follow a

completely separate path. Direct burial may be ruled out if one demands that the circuit be highly reliable, because of the impossibility of making rapid repairs on a buried line.

Several installation options are possible for electric pipelines. Overhead, buried, and placing the line in an accessible (probably mostly underground) service corridor are recognized options. Elevating the electric pipeline (the project would look more like elevated train tracks than a conventional power line) has advantages in terms of accessibility for maintenance and repair compared to burying the line. An elevated line would, however, have the greatest aesthetic impact and would also be at greater risk of accidental or malicious damage. An elevated line would also experience greater temperature variations, which would cause design complications.

Buried lines have well known problems with maintainability, reliability, and time required to repair a fault condition. Also, buried lines experience surface shear loads due to thermal expansion and contraction that could lead to fatigue problems. (Buried rigid lines would require close-spaced expansion joints to overcome this difficulty). Finally, buried lines are subject to surface corrosion and damage during installation that may go undetected and cause problems later.

The preferred installation method for electric pipelines is to mount the electric pipelines in an accessible (preferably climate-controlled to minimize stresses due to thermal expansion and contraction), partially underground service corridor. The roof of the service corridor should ideally be rapidly removable to allow for access by cranes to the pipeline itself for repairs, if this should be required. (A fully buried corridor is less desirable because cranes could not be effectively used in construction and repair of the electric pipeline.) If two circuits (i.e., 4 electric pipelines) share the same corridor, then it would be essential to guarantee that no feasible accident could simultaneously knock both electric circuits out of service simultaneously. (One implication of this is that parallel lines would have to be split so as to cross navigable rivers at different points, because of the possibility of damage to the bridge structure by a barge, for example.)

The design requirements outlined above for the electric pipeline service corridor are highly compatible with dual use of the corridor roof as a bike trail. Bikes, unlike trucks or trains, are incapable of experiencing violent accidents that could damage the corridor or the pipeline. Most routine maintenance and inspections would occur inside the corridor, with the roof on. The waste heat escaping from the electric pipelines in such a corridor is significant, and would have to be removed to allow the temperature inside the corridor to be controlled. This could be accomplished by mostly passive means.

Such a low aesthetic impact, environmentally benign installation method for an electric pipeline project increases the possibility of gaining the support of environmentalists and

outdoor enthusiasts for the concept of electric pipelines. At the same time, the very low electrical resistance and high reliability of the pair of electric pipelines, and the maintainability due to placing the pipeline in an accessible service corridor, are advantageous from the utilities' point of view (and from the point of view of national energy policy).

The service corridor itself would be a major cost in the proposed project; net cost over direct burial of the line is estimated to be about $550,000/kilometer, or about $2.75 billion for a coast-to-coast power line (this portion of costs is not very sensitive to the size of the electric pipeline at all in the size range we are considering here). To put this in perspective, this amounts to about the cost of two modern 1 gigawatt power plants whereas the coast-to-coast electric pipeline could carry more than 100 times this amount of power. (Such a coast to coast link would delay the need for at least 90 gigawatts of new power plant capacity by allowing sharing of existing capacity, saving ~$130 billion.)

A service corridor has the advantage of a very long useful life compared to most other utility investments, such as power plants. Such a corridor would remain a valuable resource long after the electric pipeline per se is obsolete. The existence of such a service corridor would substantially reduce the future cost of creating parallel lines of all kinds, including telecommunications and superconductive grid lines.

The concept of building an HVDC grid based on electric pipelines is one of those “out of the box” ideas that people often say are desirable, yet are equally likely to attack as impractical without actual examination. It is a visionary concept that pulls together several different (and in some cases contradictory) goals; for example, the proposed grid would be good for both renewable energy and nuclear energy projects. It gets right to the core of a common misconception of most environmentalists, who for the most part advocate getting “off the grid” as a desirable goal of energy policy. It is my belief that a robust and capable electric grid is an essential enabling technology that will allow wind and solar power to vastly increase their share of the total US energy pie. And, I have been unable to visualize any alternative to placing major transmission lines underground if the goal is to make our electric grid highly resistant to terrorist attack.